Towers for telescopes with extreme stability, active or passive?

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ABSTRACT

High-resolution telescopes require a mechanical stability of fractions of an arc second. Placing such a telescope on top of a tower will improve the local seeing. An open transparent tower of framework minimizes the upward, temperature disturbed air flow. The tower platform has to be extremely stable against rotational motions, which have to be less than fractions of an arc second, unusual in mechanical engineering. Active systems can improve the stability. However, they need sensors for position measurements, active actuators and a control loop. The performance is limited by the available signal-to-noise ratio. Consequently, improvement of the passive stability of large tower structures will significantly contribute to the final stability. Special geometries in steel framework can reach extreme passive stability of a tower platform, particularly against rotational motions. There are several groups of basic geometries, which lead to solutions and we will give a systematic description. The proposed towers can be welded or screwed together from smaller parts. This makes a construction in adverse environments like the Antarctic region within good reach.

Keywords: telescope towers, mechanical stability, high-resolution telescopes, local seeing, framework geometries, Antarctic telescopes, solar telescopes, gossamer structures

1. INTRODUCTION

Optical telescopes require a high stability, particularly high resolution telescopes. Locating such a telescope on a tower, which lifts the optics above the temperature disturbed air layer near the ground, has additional advantages. Wind has an important influence on this ground layer. Of interest is the contrary effect of the wind in different situations.

For solar observations the presence of wind has a positive effect on the seeing. The sun heats the ground and, as a consequence, a layer of forced convection develops near the ground with large temperature variations, which deteriorate the image quality. Without wind these warm air plumes are hundreds of meters high. On the contrary, a wind breeze mixes the air and keeps the layer of forced convection low enough, so that a telescope placed on a tower platform will reach air with a homogeneous temperature. On a good location, like the Observatory on Roque de los Muchachos on the Canary Island La Palma, a typical minimum tower height is 15 meter.[1] Sharp images can be obtained with a wind speed in the range of 2 to 20 m/sec.

However, for nighttime (winter) observations on Antarctica the presence of wind has a negative effect on the seeing. There the air near the ground is much colder than a few tens of meters higher because of heat loss of the ground by infrared radiation to the sky. Without wind, this situation would give a stable temperature gradient. Very often there is wind, which produces a ground layer with strong temperature fluctuations. Most of the time nevertheless, this temperature disturbed layer is only a few tens of meters thick. A typical minimum tower height on the location of Dome C is 30 m.[2,3]

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From the preceding we can conclude that for solar observations both wind and tower are necessary to obtain sharp images. For Antarctic nighttime observations wind is unwanted. However, a tower enables sharp images despite the presence of wind. In both cases, the tower platform has to be extremely stable against rotations and vibrations induced by wind. In addition, an open transparent tower of framework minimizes the upward air flow – caused by wind against the tower structure – of temperature disturbed air near the ground towards the telescope on the platform. For an Antarctic tower, there is the additional advantage of the lower weight of a steel construction compared to a massive concrete tower, which will make the transport to the location and the foundation on the ice more feasible.

2. ACTIVE SYSTEMS

At the first glance, a light weight steel tower seems to be not so stiff and the application of an additional stabilization system for the platform appears to be obvious[4].

One could apply an active system developed for platform stabilization on ships. It is based on two or three axes with hydrostatic bearings and hydraulic motors for the rotations. The hydrostatic bearings have no friction. The hydraulic motors are based on a design with a rotor, carrying partition plates which move along chambers in the stator, see Fig. 1. At one side of each chamber an opening is made for the entrance of the oil under high pressure. At the other side of each chamber there is a second opening where the oil flows back to the pump. Springs in the rotor press the partition plates against the chamber wall in the stator. The direction of rotation is reversed simply by interchanging the high pressure entrance with the flow-back opening, realized with proportional hydraulic valves in both directions. The partition plates have a certain friction, but this is not al all a problem for normal applications of platform stabilization. Hydraulic systems have an extreme large power in a small volume because of the very high pressure and the large volumes which can be pumped. Consequently, the system is highly dynamic and can counter-move large masses during the heavy motions of a ship in a storm.

Telescopes require a high pointing precision. Consequently, this precision is also desirable for the platform stabilization. At this point, a precise analysis of the friction of the partition plates becomes necessary. A typical behaviour of mechanical friction is its sudden decrease when the motor starts. Every drive system is in principle a mass-spring system, which is illustrated in Fig. 2a. The picture shows a linear motion with the belonging differential equation underneath, followed by the corresponding equation for a rotational motion.

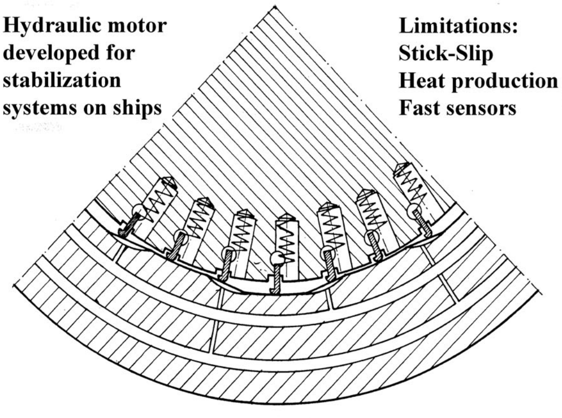


Fig. 1

Fig. 1. Hydraulic Motor

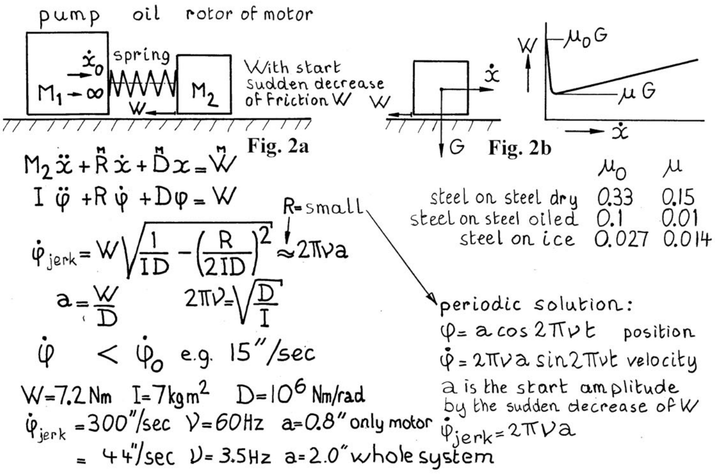


Fig. 2a,b. Stick-Slip principle

The principle works as follows. Each drive system is in fact a spring with finite stiffness D. At first, the spring has to be tensioned to overcome the static friction force W_0 before a motion can start. With the start of the motor, the friction force W decreases suddenly, see Fig. 2b. Consequently, the spring can relax and build up a velocity which is higher than the desired velocity, until the spring is relaxed to the force required for the dynamic friction W_d . The position of the mass M_2, respectively shaft, can be in front of what is desired and the motion stops till the spring again is tensioned sufficiently for the next motion step. This phenomenon is called stick-slip motion: it sticks till the spring is tensioned and then it slips. In practice, it is difficult to suppress this stick-slip motion with a closed control loop, even with a precise position measurement at M2. It is inherent to the step function of the mechanics between the actuator=motor and the object to be positioned.

Actually, this hydraulic system was considered for use to two optical siderostat telescopes of 50 cm aperture for stellar interferometry tests. Some rough calculations for the motors only gave jerks with an amplitude a = 0.8 arcsec and a velocity v = 300 arcsec/sec. A precise computer analysis of the whole hydraulic system by its manufacturer gave for this application jerks with a = 2 arcsec and v = 44 arcsec/sec. The important factor for the spring flexibility is the compressibility of the oil. The stiffness D decreases for the whole system, including the conduct-pipes. Consequently, the amplitude a increases and the velocity v decreases. Moreover, the increase of the inertial moment I and the damping R for the whole system causes a decrease of the velocity. However, increasing I and R is not a remedy to avoid stick-slip, because then the system becomes too slow.

A precision of 2 arcsec means 50 cm on a distance of 50 km and the typical customers for this type of platform stabilization are completely satisfied with this precision. However, for astronomical high resolution observations a stability of 0.1 arcsec is required. This case illustrates that active systems for moving large masses will give difficulties in the region of sub-arcsec precision. Also hydraulic cylinders and electro-mechanical actuators can show stick-slip effects.

Greases with solid lubricants like Molybdeen disulfide (MoS_2) can largely reduce stick-slip in plain bearings. However, it is not a suitable method for hydraulic systems. We did tests with oils and found that they always show stick-slip, even with high pressure additives. The addition of solid lubricants to hydraulic oils is not recommended. A possible way out would be the design of hydraulic motors and/or actuators (= cylinders) without sealing and to accept a certain oil stream through slits between moving parts like in hydrostatic bearings. One can think of several piston rings placed behind each other, like the piston springs in an internal combustion engine, but of course here the rings have a small slit with the cylinder wall.

We did not proceed on this way because of another disadvantage of the hydraulic systems: the oil pump with drive motor produces a lot of heat and even the oil is heated. We intend to minimize the heat production in and near the telescope, because any heating of the air in the optical beams will deteriorate the image. In the case of high-resolution observations a temperature fluctuation of 0.1 ºC of the air within the main beam is already harmful.

Concerning the commonly used hydrostatic bearings, we found that large roller bearings under moderate preload are an excellent alternative.[5]

An additional problem for an active platform stabilization system is to find inclination sensors which are sensitive in the sub-arcsec region and at the same time fast enough to follow wind vibrations. The required response of the sensor is typically up to 10 Hz. Fig. 3a and 3b show typical wind gust spectra.[6] Vertical gustiness – see Fig. 3b – is important for tower platforms because of their large horizontal surface exposed to the wind. The spectrum decreases rapidly between 1 and 10 Hz. Sensitive gravity-referenced inclinometers have a resolution of 0.1 arcsec, but have a –3dB frequency of

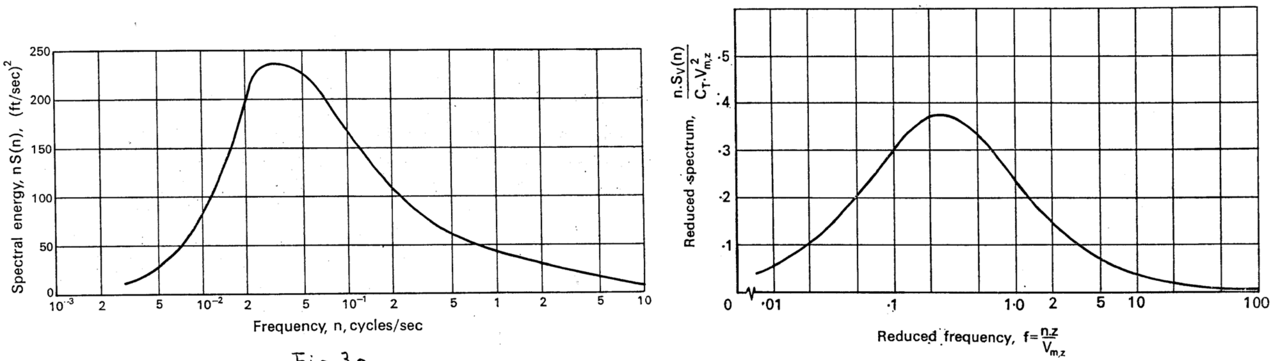


Fig.3a

Fig.3b

Fig. 3. Spectra of gustiness in strong winds: a) horizontal gustiness; b) vertical gustiness

only 0.5 Hz. The resolution decreases to 1 arcsec for a type sensitive to 10 Hz. In addition, a much larger non-repeatability can occur: max. 2.8 arcsec for the 0.1 arcsec resolution type and 4.1 arcsec for the 1 arcsec resolution type.[7] A way out for the sensor problem may be the application of ring laser gyros or fiber optical gyros.[8] Further investigation is needed to establish if these are fast enough with the required precision.

Since a couple of years, many telescopes are equipped with a correcting system for the wavefront disturbances caused by the temperature fluctuations in the earth atmosphere, i.e. the seeing. Such an Adaptive Optics (AO) system consists of a deformable (AO) mirror and, in addition, a tip-tilt mirror to correct the tilt of the wavefront. The tip-tilt mirror could also be used to correct the rotations of the platform.

This mirror is relatively small-sized and placed in the secondary optical system near an intermediate pupil image. The mirror can be driven by piezo electric actuators. It can correct small tilts of the wavefront in a fast way. However, there are two limitations when the tip-tilt mirror in addition has to correct platform rotations :

1. The maximum amplitude within the limited range of the tip-tilt mirror, because of its high resolution and precision.
2. The high-frequency amplitudes have to be not significantly larger than those of the seeing, because otherwise the correction of the seeing is negatively influenced. The AO seeing correction is limited by signal-to-noise and the end result is better when the disturbances in the input signal are smaller.

These facts and the problems with active systems with large masses lead to the search for towers of which the platform rotations are already minimized using passive means. For such towers the remaining fast rotations are smaller than the resolution of the telescope, or they are at least so small that the used seeing correction system can easily handle them. Slow rotations, for instance due to temperature changes, are compensated by the guiding or tracking system of the telescope.

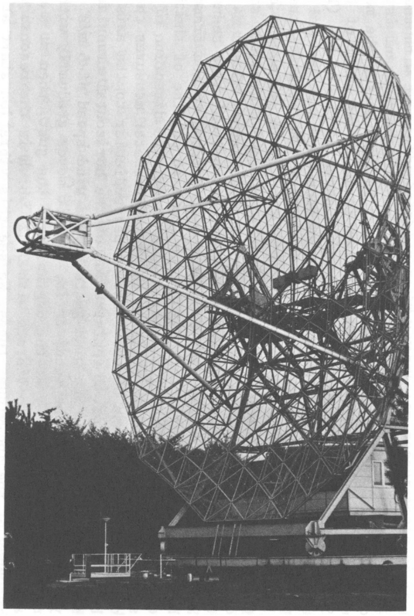
Fig. 4. Dutch Open Telescope (DOT) tower on La Palma:
a) *left*: summer: tent dome open for solar observations; b) *right*: winter: tent dome closed, ice in ladder/elevator framework

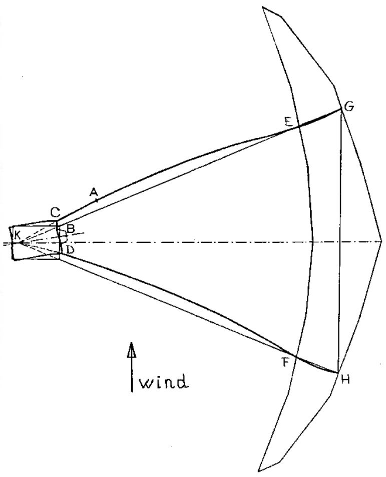
3. PASSIVE METHODS TO INCREASE THE STABILITY

The tower of the Dutch Open Telescope (DOT), see Fig. 4a and 4b, is the first tower for which the important rules for an extreme platform stability are applied. In the following we will use this tower as an illustration of these rules.

3.1 Rule 1: Use everywhere triangles without small angles

When this rule is applied, push- and pull-forces between the corner points will not cause bending of the connecting beams. Fig. 5a shows the four legs carrying the receiver of the 25m radio telescope at Dwingeloo, the Netherlands. Fig. 5b shows how these four legs deform when the wind blows against the structure. Point B in the figure is the focus point with the antenna of the radio receiver. The box behind B houses the electronics and cooling machine. The stiff point is K, which is the virtual top point of the triangle KGH. The trapezium CDGH, however, is not stiff, because it is not split-up in triangles. With hard wind point B moves a few mm: ≈ 5 mm with a wind velocity of 20 m/sec, Beaufort 8, when the observations were stopped. For the mechanical strength of the radio telescope and for undisturbed radio observations these deformations are not a problem. The telescope has originally been built for the 21 cm hydrogen line and the shortest wavelength used is 6 cm. However, for an optical high-resolution telescope with wavelengths down to 0.4 μm this size of deformations is disastrous. The deformations were also measured with optical interferometers which confirmed our calculations.[9,10]





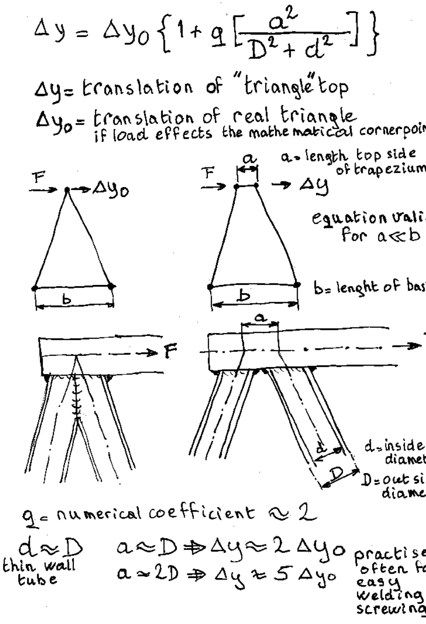
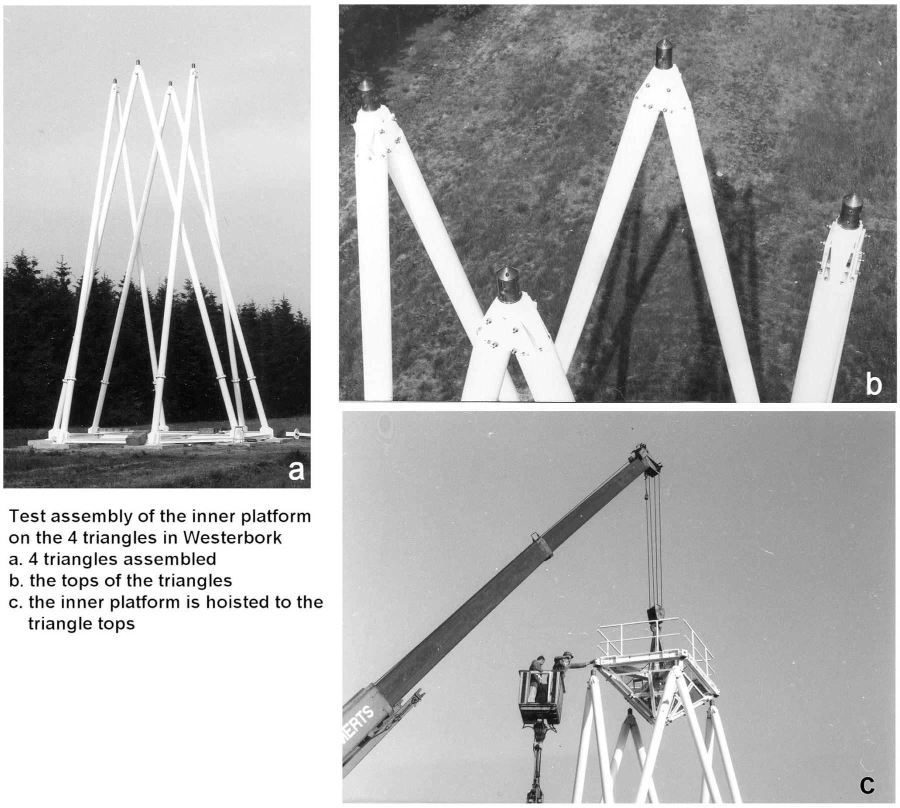


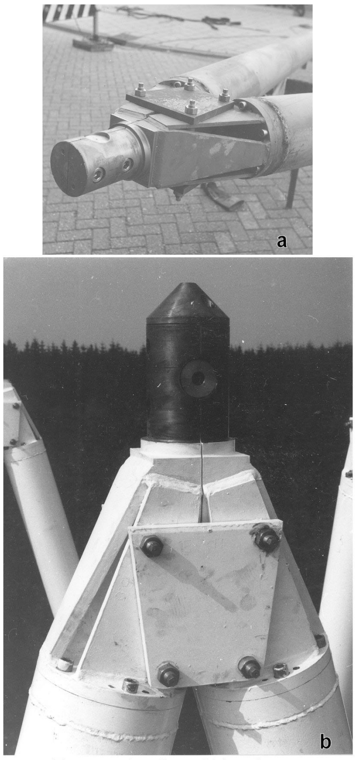
Fig. 5. a) *left*: Four legs carrying the receiver of the 25 m radio telescope at Dwingeloo, the Netherlands.
b) *middle*: Deformation of these four legs under wind load.

Fig. 6. *right*: The principle of the calculations of the transition from stiff triangle to weak trapezium.

Fig. 6 illustrates the principle of the calculations of the transition from stiff triangle to weak trapezium. These calculations were confirmed by measurements with optical interferometers of four-leg models.[11] For the stiffness of the overall construction it is very important that the center lines of the connecting tubes or beams go through a single point. A deviation equal to the diameter of the tubes will already reduce the stiffness with a factor of two. This reduction factor goes quadratically with the deviation. The construction of corner points with center lines going through a single point gives more work, but is feasible. Fig. 6 illustrates this for a welded connection. The same holds for screwed connections. This is illustrated by Fig. 7 and 8 for the DOT tower which in principle consists of 4 triangles carrying the platform. The larger amount of work is rewarded with the advantage of a high stiffness and strength combined with a low weight. In addition, the surface exposed to the wind becomes small, hence one gets the advantage of smaller wind forces and a better seeing. That also the increase of strength can be a good reason to use the proposed triangle construction was demonstrated in the construction of the framework for the staircase and elevator. At the La Palma Observatory the framework can be full of ice, see Fig. 4b. To withstand a hurricane when filled with ice, it was necessary to construct all the welded connections as in the left-hand example of Fig. 6.



Test assembly of the inner platform on the 4 triangles in Westerbork
a. 4 triangles assembled
b. the tops of the triangles
c. the inner platform is hoisted to the triangle tops



Top construction of triangle
a. fabrication in Delft
b. test assembly in Westerbork

Fig. 7. *left*: DOT tower: 4 triangles carry the platform.
Fig. 8. *right*: Screwed corner point of DOT tower with center lines of triangle tubes and platform beams going through a single point.

To obtain high stiffness the smallest angle of a triangle must be larger than a minimum value θ and the largest angle smaller than π-θ. Very stiff constructions require about $\theta \geq 30^\circ$. How this principle works out in practice and how frameworks can be built in a stiff way by combining and piling triangles is indicated in the appendix of an article about the construction outlines of the DOT telescope.[12]

3.2 Rule 2: Special attention to the design of corner- and foot-points

The design of the corner- and foot-points require special care because the maximum allowed deformations are smaller than the machining precision and flanges are in general not stiff. This is illustrated in Fig. 9 with a foot of the DOT tower as an example. The problem that all center lines of the connection have to go through a single point is discussed in subsection 3.1. In addition, it gives often several advantages to design the corner- and foot-points in such a way, that the beam- or leg-ends are fixed. This increases the resonance- or eigen-frequency for transverse vibrations of the beams or legs, see subsection 3.3. The shortening of a beam or leg by the transverse bending under wind load reduces significantly, up to a factor of 25, between the case in which both ends of a straight beam are pin-connected (hinges) and the case in which both ends are fixed. Also the buckling strength of a beam or leg increases significantly. This has no influence on the stiffness but has an advantage for the strength.

3.3 Rule 3: No low eigen-frequencies with low damping in the structure

From Fig. 3b we learned that the energy in the wind variations decreases rapidly between 1 and 10 Hz. Consequently, structure parts with an eigen-frequency ≥ 10 Hz will not come into resonance due to wind buffeting. Vortex oscillations[13] (which produce the so-called Von Kármán eddies[14]) can give higher frequencies, but a small damping can suppress the oscillation, because the force is small compared to the wind buffeting force. Moreover, low eigen-frequencies will show sooner vortex oscillations. The 15 m long tubes of the legs of the DOT tower with a diameter of only 245 mm have an eigen-frequency of 6 Hz for transverse vibration. For a wind velocity of 7 m/s, the frequency of the vortex oscillations becomes equal to this mechanical eigen-frequency. The geometry of the DOT tower is such, that the tubes pass each other closely near half the height of the tower. Consequently, rubber dampers could easily be placed at half the height of the tower, see Fig. 10. A small difference between the eigen-frequency of two crossing tubes makes the dampers already effective. To this end, the eigen-frequency of one of each pair of crossing tubes is increased a little bit by small perpendicular tubes near the ground.[1] These perpendicular tubes do not disturb the parallel motion of the platform, see subsection 3.4.

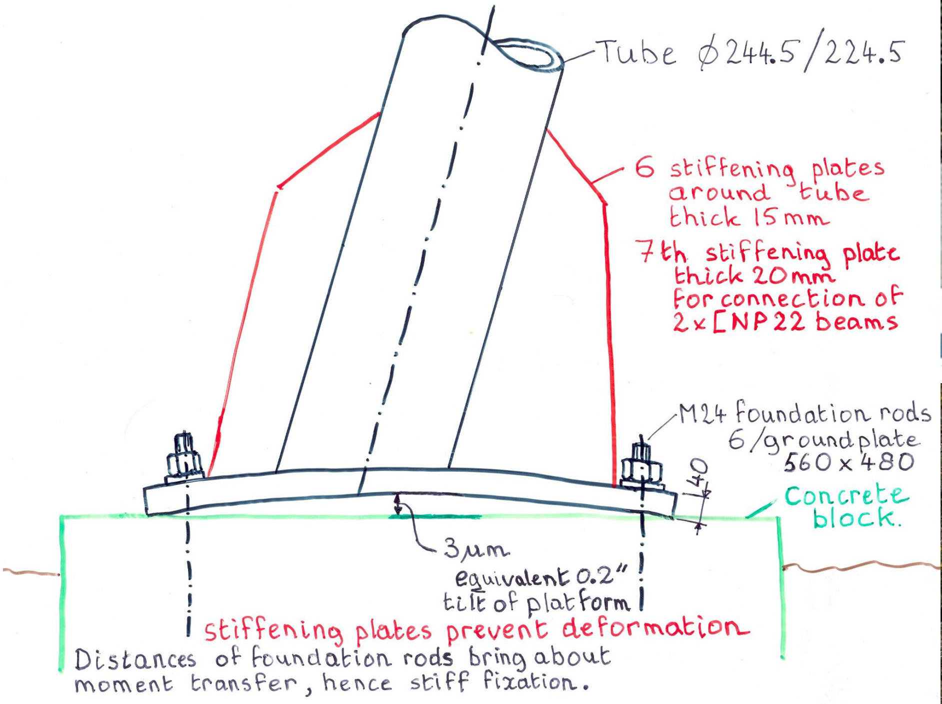


Fig. 9. *left + top right*: Design of the feet of the DOT tower. Designed with special attention, because the maximum allowed deformations of 3 µm - equivalent to 0.2" tilt of the platform - are smaller than the machining precision. This care is required for all corner-points.

Fig. 10. *bottom right*: Damper of 2 rubber plates in the middle of the long tubes, where the latter pass each other closely.

Low frequencies can easier be compensated by an active system like a tip-tilt mirror. However, it is a contra-productive method to decrease the eigen-frequency for this reason, because a decrease of the eigen-frequency ν requires a quadratic decrease of the stiffness D or a quadratic increase of the inertia M or I (see formulas in Fig. 2a). In both cases the risk for resonance vibrations of the structure increases. Subsystems in the tower, like a staircase house, an elevator and even a fence, can also show low frequencies with low damping, which disturb the telescope observations. Open ends of tubes can become organ pipes in the wind. Consequently, all subsystems have to be examined carefully concerning this rule, even if they are not a part of the main structure.

3.4 Rule 4: The geometry for a motion of the platform parallel to the ground

Astronomical objects are far away and consequently a pure translation of the telescope does no harm. Any construction will show a certain deformation under wind load to produce a counter-force. The trick is to choose the geometry of the construction in such a way, that the counter-force to the wind is, as good as possible, generated by a pure translation of the platform relative to the ground.

Elements for parallel motion to the ground are:
1. *Vertical posts*. In both horizontal directions, x and y, the construction is weak, but in the vertical direction z it is stiff. A force on the top point of a vertical post with horizontal component gives a large deflection in horizontal direction, but the vertical component of the force gives only a very small vertical deflection. Consequently, the motion of the top point is nearly parallel to the ground.
2. *Isosceles triangles in a vertical plane*. In the plane of the triangle the construction is stiff, both in horizontal and vertical direction. Perpendicular to this plane it is weak, but the motion of the top point is nearly parallel to the ground just as for the case of the vertical posts. The isosceles triangle will carry horizontal wind force on the platform in its plane because of its stiffness in that direction. In a weak direction it has not to carry anything, because the wind load on the platform in that direction will be carried by other parts of the construction which are stiff in that direction. Special to the isosceles triangle is, that the deflection of the top point in its stiff plane under a horizontal load is also horizontal. This holds for the assumption that the material area of the cross section of both legs of the triangle is equal, which is of course the case if both legs are tubes or beams made of the same material. Under a horizontal load one leg gets a pull force and the other leg a push force of equal strength. Consequently, the elongation of one leg and the shortening of the other are equal and a little geometry leads to the conclusion that the deflection of the top point is horizontal.
3.*Isosceles multi-legs or cones with a high enough degree of symmetry*. These are stiff in all horizontal directions and give a deflection in the same direction as the horizontal load, based on the same principles as given for the isosceles triangle.

A combination of enough elements for parallel motion results in a platform which moves parallel to the ground and which is very stiff against rotations around all horizontal axes. However, the platform needs also to be stiff against rotations around the vertical axis. This last requirement is fulfilled when at least three isosceles triangles are used, which are not all three parallel or nearly parallel. In addition, the top angles of these triangles have to be large enough, the angle depending on the required stiffness. Top angels of 30º or more result in a very high stiffness. It may be compared to the last paragraph of subsection 3.1.

3.5 Influence of the height of the tower on the design

The 15 m high DOT tower uses 4 triangles, see Fig. 4 and 7. A tower design using 3 triangles is easy to erect on an uneven surface[9] and is applied to a small tower of 7.5 m height at the South Pole and – in the same order of size – to the site testing towers for the Advanced Technology Solar Telescope (ATST) site selection.[1] The disadvantage of using only 3 triangles is that the triangle-shaped platform has little space beside the telescope. Other possible minimum-combinations are: 1 multi-leg + 1 triangle + 1 post and 2 multi-legs + 1 post.

When the height of a tower becomes significantly higher than the 15 m of the DOT tower, the construction of isosceles triangles of single tubes will get the disadvantage of low eigen-frequencies of the tubes for transverse vibrations, see Table 1 in ref.[1]. Efficient damping against wind buffeting becomes a must, which may become a problem depending on the geometry of the total tower design. Anyhow, it is wise to avoid low eigen-frequencies and advisable to investigate other possibilities.

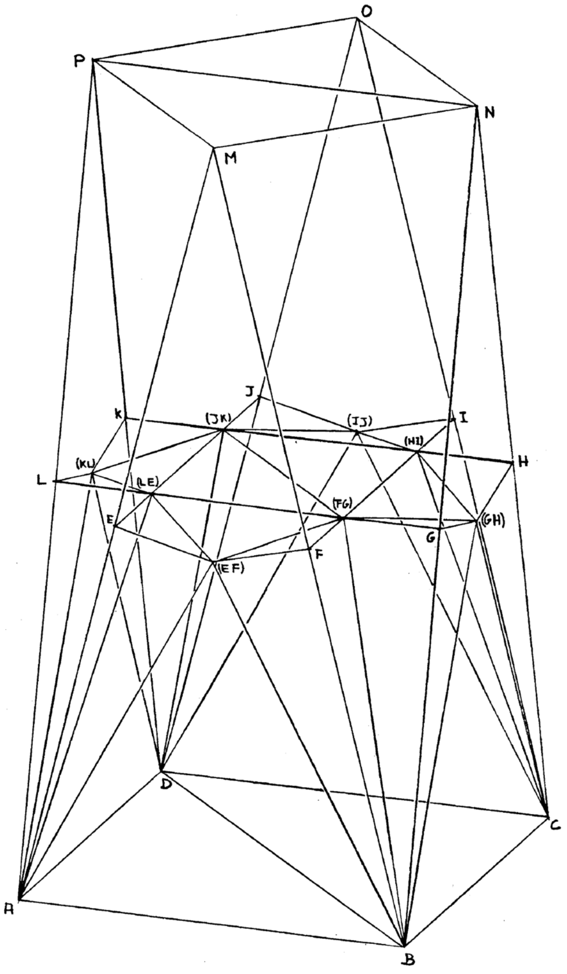
A solution that does not work is to put a second tower with parallel platform motion on the platform of the first tower with parallel platform motion. A wind force on the second platform causes a large moment to the base of its tower. This moment is transmitted to the first platform, which will tilt. As a consequence, the second tower will tilt as a whole, including the second platform.

A solution that works is to stick to the principal geometry with elements of parallel motion from the ground to the platform at the top, in combination with additional supporting points along the long elements to avoid transverse vibrations. However, these additional supporting points could bring forces along the elements of parallel motion and in that manner disturb the parallel motion. These disturbing forces can originate from moments on lower levels, induced by the wind force on higher levels. Consequently, the trick is to make the additional supporting points in such a way that only forces are transmitted perpendicular to the tube or beam of the parallel motion element and no forces along the tube or beam.

An auxiliary tube or beam *perpendicular* to the main tube or beam of the parallel motion element forms such an additional supporting point. The length of this auxiliary tube or beam has to be large enough compared to the area-moment of its cross section, such that the bending force of the auxiliary tube or beam is negligibly small when its end follows the longitudinal elongation or compression of the main tube or beam. The other end of the auxiliary tube or beam has to be fixed to a separate framework or insensitive part of the main framework from which it gets enough longitudinal stiffness or damping to avoid the transverse motion of the main tube or beam.

3.6 Models for high towers

Fig. 11 shows a four-triangle tower with additional framework until half-way the height of the tower. Auxiliary tubes lead from the additional framework to the middle of the main tubes of the four isosceles triangles. Each point half-way a main tube is connected with two of such auxiliary tubes in order to suppress transverse motion for both dimensions perpendicular to the main tube.



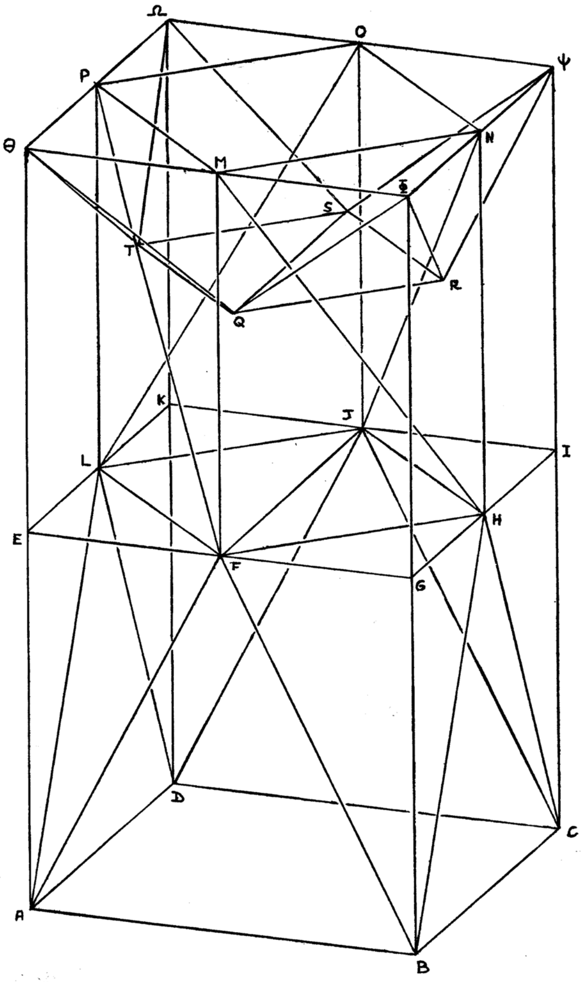


Fig. 11. *left*: Four-triangle tower with additional framework until half-way the height of the tower, not disturbing the parallel motion of the top platform.

Fig. 12. *right*: Principle of a double tower: the outside tower keeps the platform parallel to the ground; the inside tower makes the platform stiff against translation.

A next step is a concept in which also the top points of the elements of parallel motion are fixed in the horizontal directions by auxiliary tubes or beams. The other ends of these auxiliary tubes or beams are fixed to a separate framework, which forms in a certain way a second tower. The translation stiffness of the top of this second tower is made very high (rule 1: everywhere triangles). The rotational stiffness around horizontal axes of the top of this second tower needs not to be extreme high. Consequently, we can use for this second tower, so to say, a normal triangle framework without giving special attention to obtain a parallel motion without any tilt. The differences in height of the top points of the second tower are not transmitted to the top points of the main tower because of the negligibly small bending force of the auxiliary tubes or beams between the first and second tower.

A design with only vertical posts as parallel motion elements for the first tower can be used if the second tower prevents all horizontal motions, including rotations around a vertical axis. Of course, vertical isosceles triangles and multi-legs can still be used, but the use of only vertical posts – at least three – for the first tower makes it possible to obtain an extreme stable platform.

Fig. 12 shows the principle of a double tower in a design of two stories. The main tower has 4 vertical posts as elements for parallel motion: AEΘ, BGΦ, CIΨ and DKΩ. These are located at the periphery for maximum stiffness of the platform against rotations around horizontal axes. The second tower consists of the triangles ABF, BCH, CDJ and DLA to the first floor and, from there, of the framework structure upward from FHJL to MNOP. The 4 vertical posts have only horizontal connections to the second tower. The base for the telescope is the square QRST, which is connected with 4 triangles QRΦ, RSΨ, STΩ and TQΘ to the rotationally stable platform square ΦΨΩΘ.

Fig. 13 shows a design of the same principle with an additional framework for 4 stories, which gives a further reduction of the free lengths of the tubes and beams, and consequently, the advantage of a higher eigen-frequency. This design has been proposed for the support of Large Open Telescopes, such as LOT[1] and GISOT[15].

3.7 Concept tower for Dome C on Antarctica

The concept of Fig. 13 is promising as an application to a 30 m high tower for a telescope located at Dome C on Antarctica, see section 1. A student team of Harvey Mudd College made calculations with the finite element modeling program ANSYS.[2] The proposed dimensions for the tower are:
- height 30 m, divided into 4 stories of 7.5 m
- base 12 × 12 m
- vertical posts, tubes with ∅ 273/233 mm
- all other vertical or inclined connections, tubes with ∅ 244.5/224.5 mm
- all horizontal connections dual coupled CNP24 beams with the exception of the square QRST, there CNP30 beams, because these form a base for the telescope structure.

Fig. 14 shows a further development of this concept. The stiffness in the first floor is obtained with an additional framework from the ground level. Consequently, the mid-region between the first floor and the third floor is more open than in the design of Fig. 13. This is favourable to the minimization of the upward air flow caused by wind against the tower structure, see section 1.

Fig. 15 shows a solidification of the concept of Fig. 14. The height is, as proposed, 30 m, the base 12 × 12 m. In the further development the importance of a construction with a weight as light as possible was stressed because of the transport. Calculations have to show how far we can go in applying thin-wall tubes and profiles. In Fig. 15 all vertical and inclined connections are round tubes with an outside diameter of 244.5 mm, the same holds for the four vertical posts. The minimum available wall thickness is 3.2 mm. The horizontal connections are drawn as square 240 × 240 mm. One possibility is to use square tubes of 240 × 240 mm with a wall thickness of 6 mm. Another possibility is to use dual coupled CNP24 beams, 240 mm high and each beam 85 mm wide, coupled with distance pieces. The connections in the square QRST are drawn as 300 × 300 mm, also these can be square tubes or dual coupled CNP30 beams.

At the base of the tower 4 foundation blocks measuring 2.5 × 2.5 × 6 m are drawn. They support the base triangles A-A1-A2, B-B1-B2, C-C1-C2 and D-D1-D2. In the case of a location on Antarctica these blocks can be 20 feet standard sea containers frozen into the ice ground. In the center of the tower base a small round foundation block is placed for the support of the crossing point Y of the base diagonals.

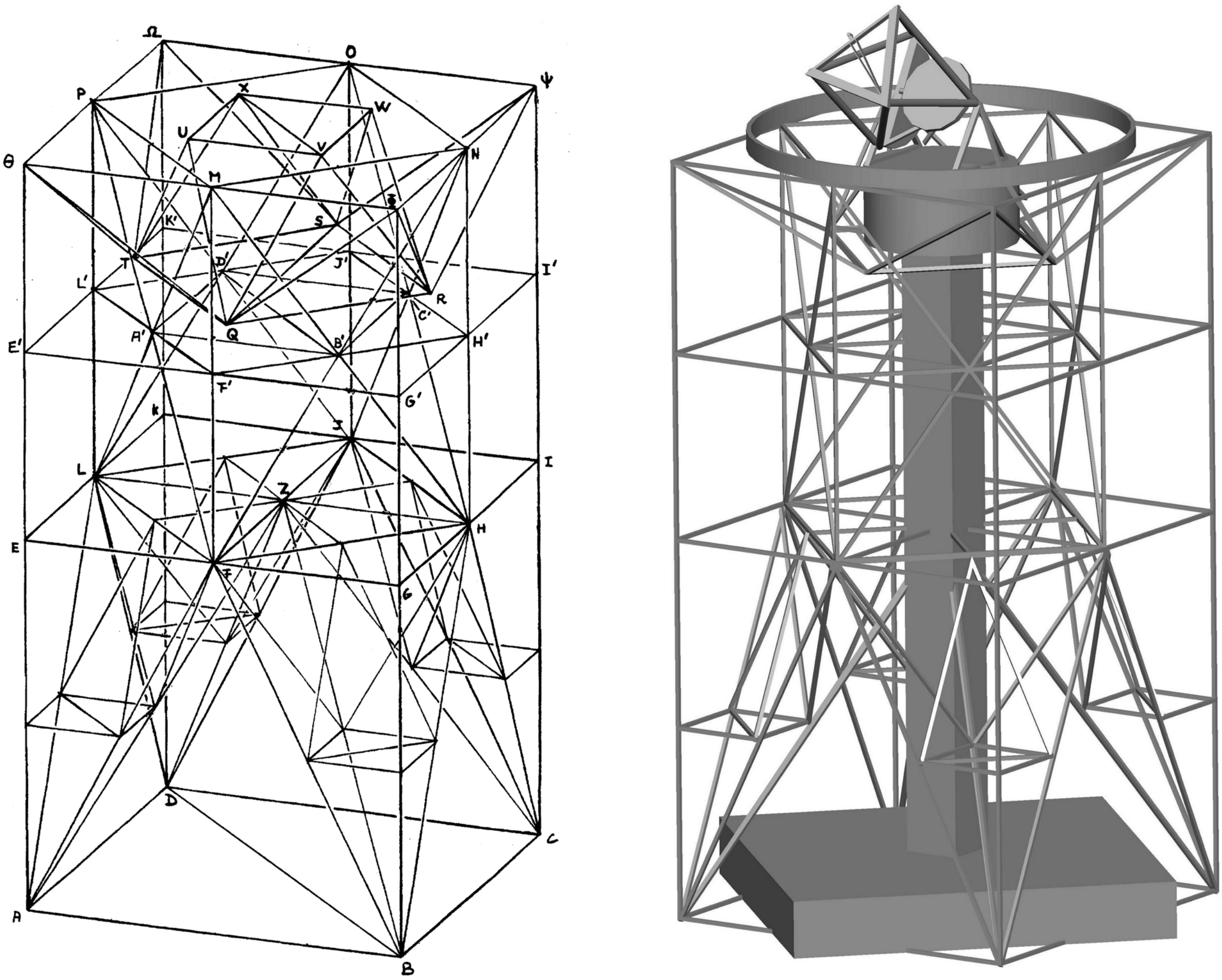
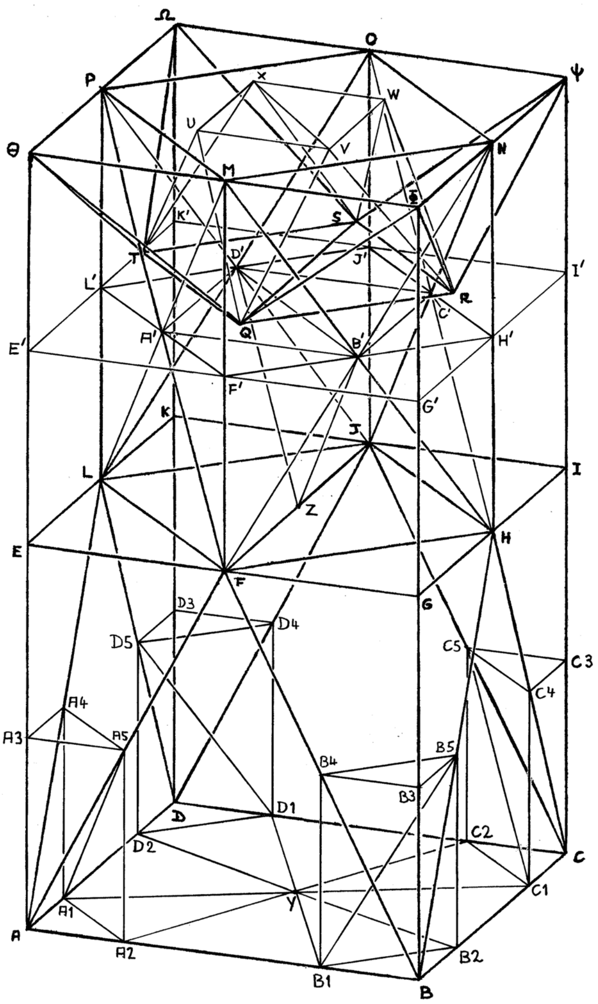


Fig. 13. Design of the same principle as in Fig. 12 with additional framework for 4 stories, which gives a further reduction of the free lengths of the tubes and beams. *left*: Principal tower design. *right*: A working-out with telescope and the options of open foldable dome, coudé focus with instrumentation room directly under the telescope, access shaft for ladder + elevator and rooms on the ground. An additional option is that the telescope light goes down through the access shaft into an optical lab at ground level, for instance for solar observations. A student team of Harvey Mudd College made calculations with the finite element modeling program ANSYS for this design: height of the tower 30 m, base 12×12 m (somewhat smaller than in this drawing: height 30 m, base 15×15 m). In the ANSYS analysis only a 2 m-class telescope of 12000 kg was placed on the platform, because, for location at Dome C on Antarctica, one of the options of operation is without dome and access shaft.

A telescope with a mirror diameter of about 2 m is drawn on top of the tower in Fig. 16. For Antarctic applications at Dome C, it may be possible to use this telescope without a protecting dome and to use only remotely controlled lids over the primary mirror and secondary optics. Snow in the traditional sense seems not to occur there, only ice deposition directly from the vapor phase.

Fig. 17 shows the same tower and telescope with a completely open foldable dome[1,15], an instrumentation room under the platform and a closed access column for staircase and small elevator. This type of set-up would also be very suitable for solar observations during daytime (summer) with the possibility of experimental set-ups in the sufficiently large instrumentation room under the platform. If desired, there is the possibility to use the column for the transport of the light beam down to a large-sized instrumentation room on the ground. The tower can carry much larger telescopes than the 2 m-class one in the drawings. Weight is not a problem, because in this concept the high stiffness goes together with a high strength. If a dome is planned, the telescope can easily be placed lower to fit into the dome by reducing the height between the top square UVWX and the square QRST.



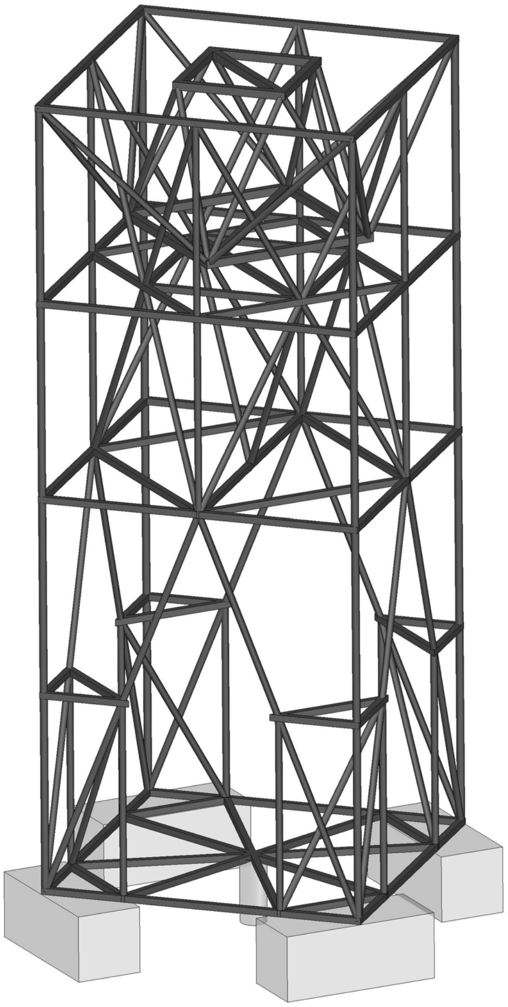


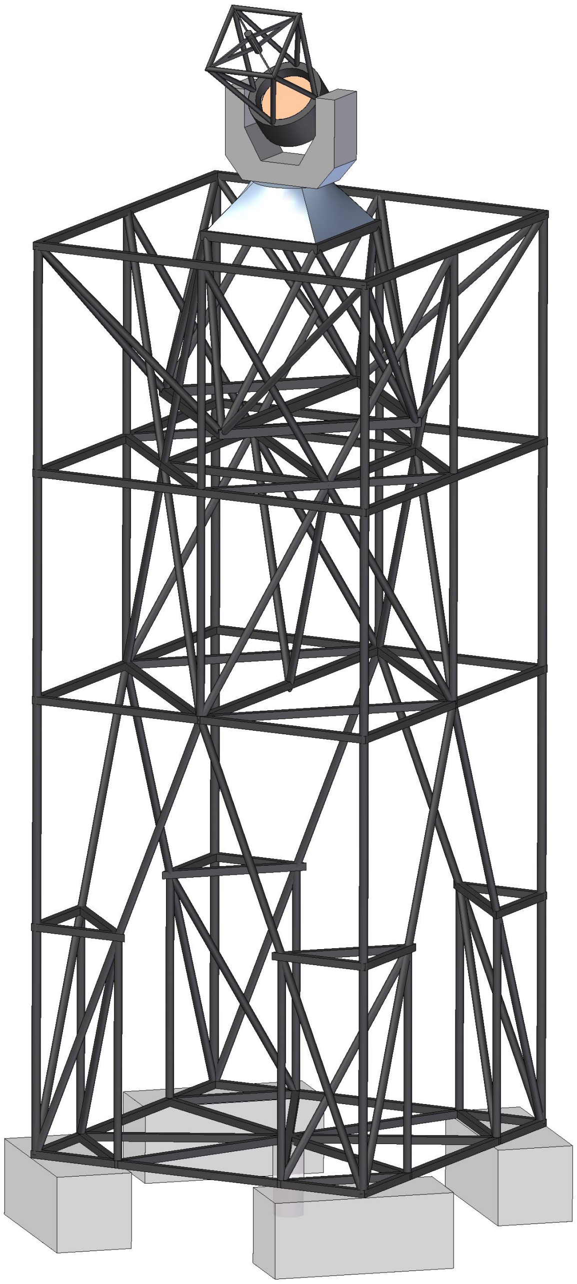
Fig. 14. *left*: Further development of the 4 stories concept. Stiffness in the first floor is obtained with framework from ground level. The mid-region between first floor and third floor is more open, favourable to minimization of the upward airflow caused by wind.

Fig. 15. *right*: Solidification of the concept of Fig. 14, but somewhat smaller. Both have a height of 30 m, the solidification has a base of 12×12 m, the concept one of 15×15 m. In the solidification all vertical and inclined connections are round tubes with a diameter of 244.5 mm, the horizontal connections are square 240×240 mm. At the base are 4 foundation blocks of 2.5×2.5×6 m, the size of 20 feet standard sea containers. In the center a small round foundation block is placed to support the crossing point Y of the base diagonals. The connections MN, NO, OP and PM are deleted in the solidification: these are not really necessary anymore, since stiffness of M, N, O and P comes from framework to A'B'C'D' in the third floor; compare with Fig. 12. The square UVWX, base for the telescope, can be increased in size in case a larger telescope is desired.

4. CONCLUSIONS

Available active stabilization systems for the movement of substantial masses, like tower platforms, have a precision of a few arcsec, a good example being 2 arcsec. The precision is limited by mechanical friction effects (stick-slip) and by the precision of fast sensors necessary to follow wind induced motions.

To correct the seeing, nowadays telescopes are equipped with an AO system, including a tip-tilt mirror. The latter can also correct tilts of the platform within certain limitations. Vibrations of 2 arcsec are large compared to the tilt induced by seeing under good conditions. Furthermore, the correction of an AO tip-tilt mirror is limited by signal-to-noise: the quality of the final image is better when seeing is smaller. Additional vibrations of the platform of 2 arcsec can produce a negative influence hereupon.



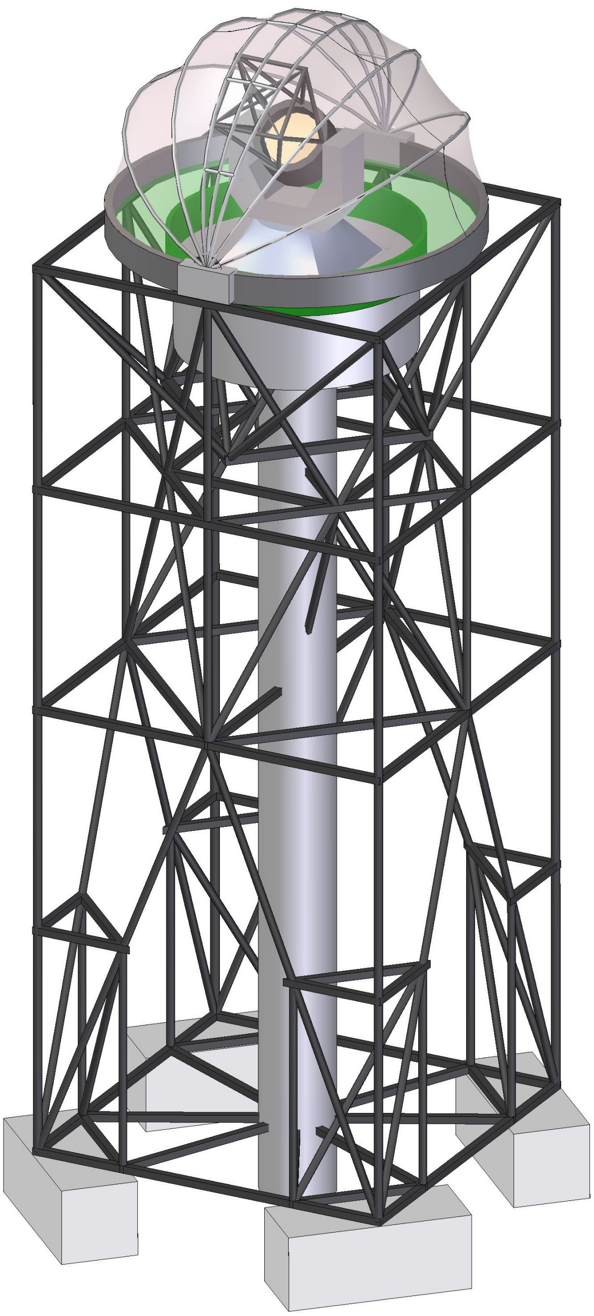


Fig. 16. *left*: The design of Fig. 15 with on top a 2m-class telescope suitable for Antarctica. A much larger telescope is possible by increasing the size of the top square UVWX.

Fig. 17. *right*: The same tower and telescope as in Fig. 16 with a completely open-foldable dome, an instrumentation room under the platform and a closed access column for staircase and small elevator.

Open framework towers have the advantage of better seeing, because the temperature disturbed air layer near the ground is not moved upward by the wind. The developed specific framework geometries can reduce the tilt of the platform by wind buffeting to the order of 0.1 arcsec with only passive means. Such a stable open tower can be directly combined with the active guiding or AO system of the telescope without the requirement of an additional active system for the tower platform.

Special framework geometries are developed, which make it possible to construct high towers in stories having platforms with extreme stability against wind-induced tilt. These geometric solutions lead to constructions, having no more mass than a normal steel framework carrying the same load. As a consequence, these constructions are extremely suited to difficult sites, for instance on Antarctica.

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